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SPACE TOOL POWER SOURCE INVESTIGATION

By Manufacturing Research Technology Division
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SPACE TOOL POWER SOURCE INVESTIGATION

by

**MANUFACTURING RESEARCH TECHNOLOGY DIVISION
MANUFACTURING ENGINEERING LABORATORY**

George C. Marshall Space Flight Center
Huntsville, Alabama

ABSTRACT

This report covers an investigation into the classes of tools suitable for use in in-space manufacture, assembly, maintenance and emergency repair. The tools are divided into categories by type of motion, class of usage, and mode of input motion. The power requirements of these tools are then studied and several power sources are discussed. An optimum power source is described, and trade-off equations are developed to cover future proposed power sources. One of the conclusions drawn in this report is that electrical power gives the most promise for space tools.

GEORGE C. MARSHALL SPACE FLIGHT CENTER

R-ME-IN-67-4

SPACE TOOL POWER SOURCE INVESTIGATION

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MANUFACTURING RESEARCH TECHNOLOGY DIVISION
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MANUFACTURING ENGINEERING LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

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SPACE TOOL POWER SOURCE INVESTIGATION

INTRODUCTION

The object of the investigation covered by this report was to study the classes of power tools to be used for in-space manufacture, assembly, maintenance, and emergency repair, and, if possible, to describe an optimum power source for these tools.

The space tools are divided into classes by types of motion, class of usage (whether repair, maintenance, assembly, or manufacture), and mode of input motion (rotary, explosive thrust, etc.).

In this report, a space tool will be broken down into three sections as follows [1]:

Power Source - a source to include power supply but not the mechanism of motion.

Prime Mover - the section that converts the energy into mechanical motion.

Attachments - those devices which attach to the prime mover section and actually perform the task.

Following classification of the tools, conclusions are drawn as to the power requirements and type of input motion. When these criteria are established, candidate power systems can be described and investigated.

A pictorial representation of approximate power source mass plus prime mover mass versus time of operation is made and used to aid in determining the optimum power source for a space tool system.

We shall now consider the classification of tools into types by Type of Motion, Type of Use, and Type of Drive Method.

CLASSIFICATION OF POWER TOOLS BY TYPE OF MOTION

This classification orders the tools by the type of motion which the tool attachment actually undergoes on the work piece. For example, when we are considering a jig saw, we consider - in addition to the reciprocating motion of the saw blade - the translational motion of the saw itself while it is making a cut. It is this translational type of motion which puts the jig saw in the translation category. Table I shows the type of motion classification.

TABLE I. TYPE OF MOTION CLASSIFICATION

Translation Type Motion	Rotary Type Motion	Other Plane Motion
<u>Saw</u> 1. Sabre Saw 2. Jig Saw 3. Circular Saw 4. Friction Heat Saw 5. Rotary-Reciprocating Saw (Bone Saw)	<u>Drill</u> <u>Hole Saw</u> <u>Rotary File</u> <u>Torquing Devices</u> 1. Nut Runner 2. Screw Driver 3. Torque Wrench 4. Aero-Space Fastener a. Huckbolt b. Betabolt c. Hi-Shear Fastener	<u>Nibbler</u> <u>Pry</u> 1. Porta-Power Driven Expander (Figure 2)
<u>Chisel</u> 1. Straight Power Chisel (For use by Tethered Astronaut) 2. Nut/Bolt Splitter		<u>Impactor</u> 1. Hammer 2. Stud Setter 3. Other
<u>Welder</u>		<u>Push and Pull</u> 1. Expander-Contractor-Porta-Power (Figure 2)
<u>Shear</u> 1. Reciprocating 2. Rotating - One Wheel 3. Rotating - Two Wheels	<u>Grinder/Sander</u>	<u>Hole Punch</u>
<u>General Drive Mechanism</u> 1. Use to drive welder or leak detector across wide smooth surface (Figure 1)	<u>Other</u>	<u>Brake/Form</u>
<u>Other</u>		<u>Clamp</u> <u>File</u> <u>Riveter</u> <u>Other</u>

Two unfamiliar tool types are given in this classification, the general space drive mechanism and the space porta-power. In Figure 1, the general space drive is shown welding a seam on a large smooth structure. It could equally as well drive a mass spectrometer leak detector or a shuttle transfer system for the astronaut. The welding attachment is shown. Other attachments, such as a mass spectrometer seam leak detector, can be used. Figure 2 shows the space porta-power and some typical applications.

CLASSIFICATION OF POWER TOOLS BY TYPE OF USE

This classification orders the tools into groups which would normally be used for in-space maintenance and repair, in-space assembly, and in-space manufacture.

For purposes of the final power source analysis, we must break the use of the tool down still further to include two more areas: tools/power sources for use within the spacecraft and workshops, and those to be used

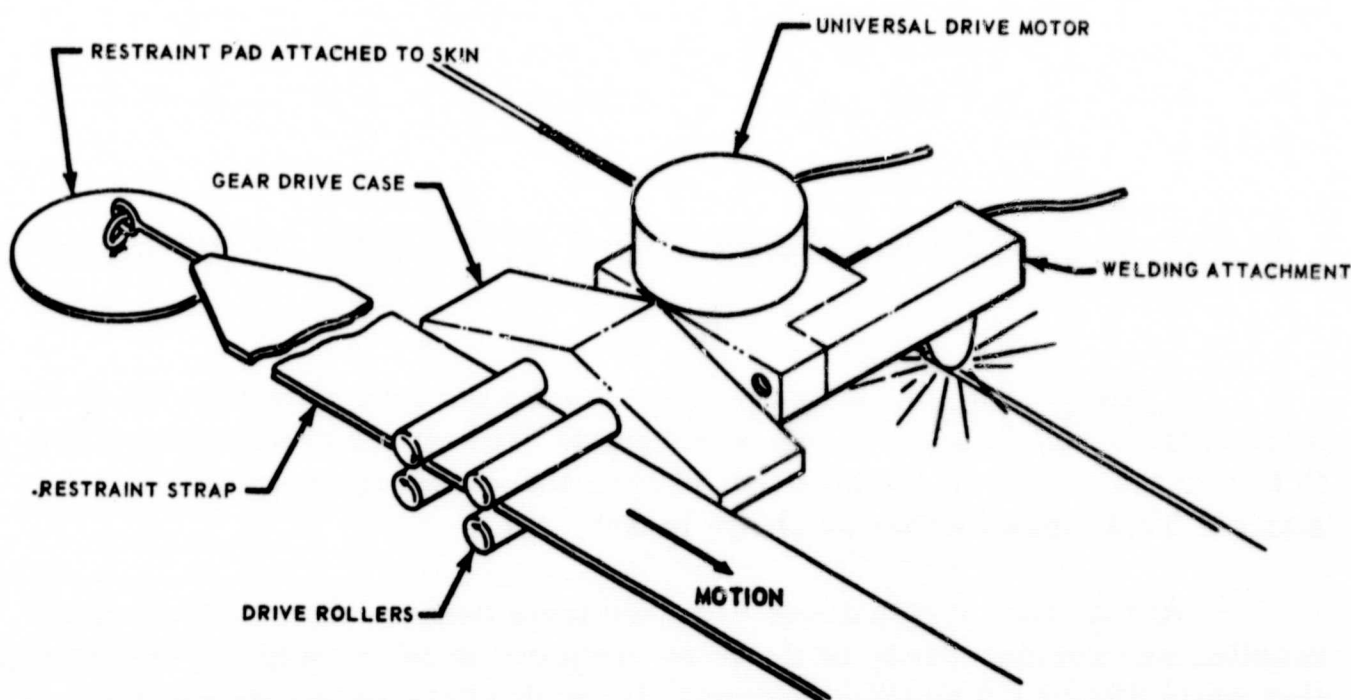


FIGURE 1. GENERAL SPACE SURFACE DRIVE MECHANISM

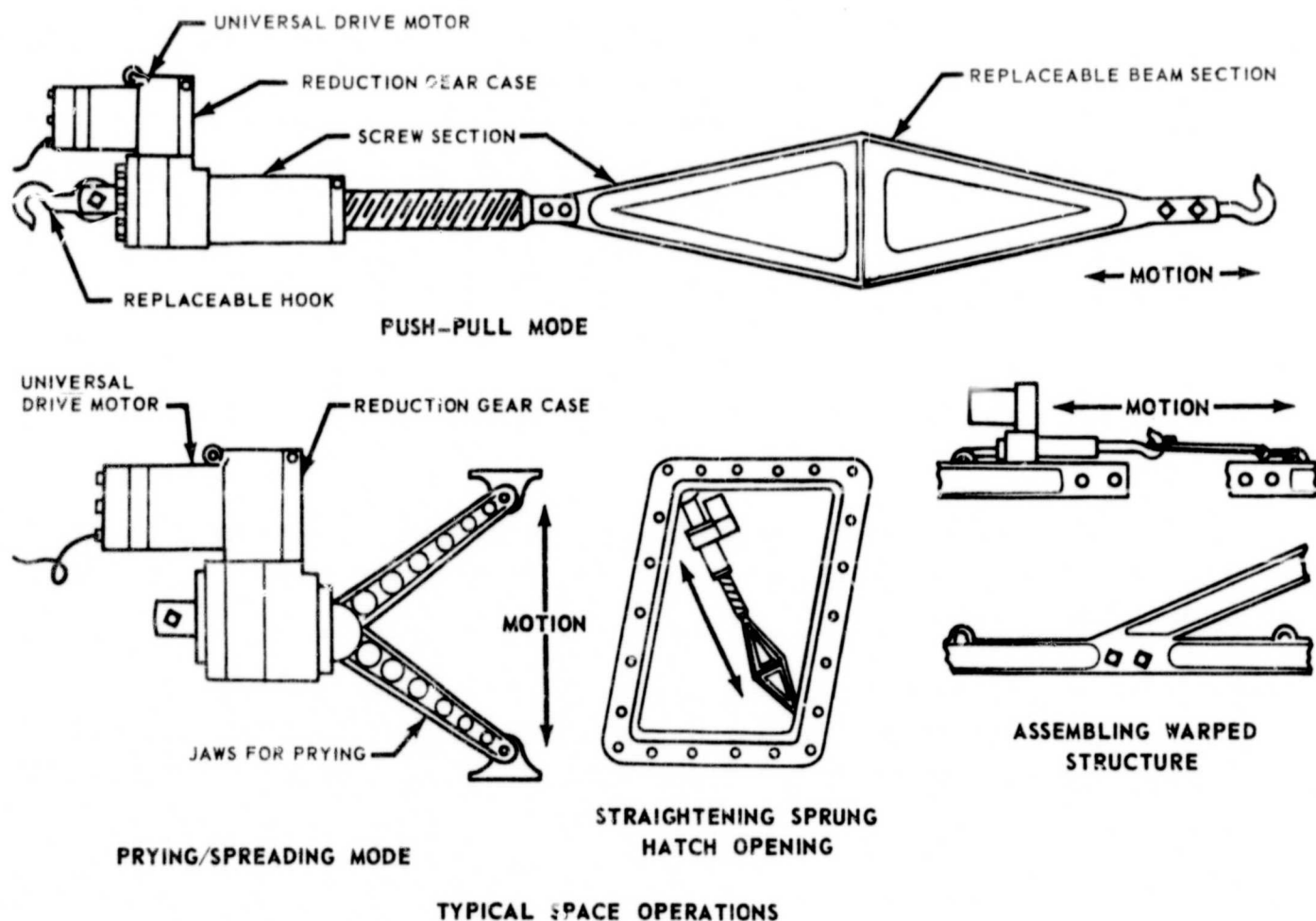


FIGURE 2. SPACE PORTA-POWER

outside. The fact will develop that, while the inside tools can be used outside, the reverse is not true; that is, safety considerations restrict certain tools and power sources to use only outside of the spacecraft. Table II outlines this in chart form.

CLASSIFICATION OF POWER TOOLS BY TYPE OF DRIVE METHOD

In this section we categorize the tools by the type of motion which the prime mover delivers to the tool attachment. The object of this classification is to find the prime mover type that powers the widest range of tool attachments. This classification is shown in Table III.

We note the large number of power tools that are driven by a rotary reactionless device. Study of the power requirements of these devices shows that while 373w (0.5 horsepower) will drive all of the rotary driven devices, in most cases, 186w (0.25 horsepower) will suffice. The impact devices absorb approximately 373w (0.5 horsepower) while the power requirements of the other tool categories depend more on the individual type of job [2, 3].

TABLE II. TYPE OF USE CLASSIFICATION

IN-SPACE MAINTENANCE/REPAIR	IN-SPACE ASSEMBLY	IN-SPACE MANUFACTURE	SPACECRAFT/WORKSHOP INTERIOR	SPACECRAFT/WORKSHOP EXTERIOR
Translational Type Motion	Translational Type Motion	Translational Type Motion	Translational Type Motion	Translational Type Motion
<u>Saw</u> 1. Sabre Saw 2. Jig Saw 3. Rotary Reciprocating Saw <u>Chisel</u> 1. Power Chisel 2. Nut Splitter <u>Welder</u> <u>Shears</u> 1. Reciprocating 2. Rotating - One Wheel 3. Rotating - Two Wheels	<u>Saw</u> 1. Sabre Saw 2. Jig Saw 3. Rotary Reciprocating Saw <u>Chisel</u> 1. Power Chisel 2. Nut Splitter <u>Welder</u> <u>General Drive Mechanism</u> <u>Shears</u> 1. Reciprocating 2. Rotating - One Wheel 3. Rotating - Two Wheels	<u>Saw</u> 1. Sabre Saw 2. Jig Saw 3. Rotary Reciprocating Saw 4. Friction Heat Saw 5. Circular Saw <u>Chisel</u> 1. Power Chisel 2. Nut Splitter <u>Welder</u> <u>General Drive Mechanism</u> <u>Shears</u> 1. Reciprocating 2. Rotating - One Wheel 3. Rotating - Two Wheels	<u>Welder</u> <u>Shears</u> 1. Reciprocating 2. Rotating - One Wheel 3. Rotating - Two Wheels	<u>Saw</u> 1. Sabre Saw 2. Jig Saw 3. Rotary Reciprocating Saw 4. Friction Heat Saw 5. Circular Saw <u>Chisel</u> 1. Power Chisel 2. Nut Splitter <u>Welder</u> <u>General Drive Mechanism</u> <u>Shears</u> 1. Reciprocating 2. Rotating - One Wheel 3. Rotating - Two Wheels
Rotational Type Motion	Rotational Type Motion	Rotational Type Motion	Rotational Type Motion	Rotational Type Motion
<u>Drill</u> <u>Hole Saw</u> <u>Torquer</u> 1. Nut Runner 2. Screwdriver 3. Torque Wrench 4. Aero-Space Fasteners a. Huckbolts b. Betabolts c. Hi-Shear Fasteners d. Others	<u>Drill</u> <u>Hole Saw</u> <u>Torquer</u> 1. Nut Runner 2. Screwdriver 3. Torque Wrench 4. Aero-Space Fasteners a. Huckbolts b. Betabolts c. Hi-Shear Fasteners d. Others <u>Rotary File</u> <u>Grinder/Sander</u>	<u>Drill</u> <u>Hole Saw</u> <u>Torquer</u> 1. Nut Runner 2. Screwdriver 3. Torque Wrench 4. Aero-Space Fasteners a. Huckbolts b. Betabolts c. Hi-Shear Fasteners d. Others <u>Rotary File</u> <u>Grinder/Sander</u>	<u>Torquer</u> 1. Nut Runner 2. Screwdriver 3. Torque Wrench 4. Aero-Space Fasteners a. Huckbolts b. Betabolts c. Hi-Shear Fasteners	<u>Drill</u> <u>Hole Saw</u> <u>Torquer</u> 1. Nut Runner 2. Screwdriver 3. Torque Wrench 4. Aero-Space Fasteners a. Huckbolts b. Betabolts c. Hi-Shear Fasteners <u>Rotary File</u> <u>Grinder/Sander</u>
Other Plane Motion	Other Plane Motion	Other Plane Motion	Other Plane Motion	Other Plane Motion
<u>Pry</u> <u>Impactor</u> 1. Hammer <u>Punch</u> <u>Riveter</u> <u>Porta-Power</u> <u>Linear Grinder</u> <u>Linear File</u>	<u>Pry</u> <u>Impactor</u> 1. Hammer 2. Stud Setter <u>Punch</u> <u>Riveter</u> <u>Porta-Power</u> <u>Linear Grinder</u> <u>Linear File</u>	<u>Pry</u> <u>Impactor</u> 1. Hammer 2. Stud Setter <u>Punch</u> <u>Riveter</u> <u>Linear Grinder</u> <u>Linear File</u> <u>Brake/Form</u> <u>Nibbler</u>	<u>Pry</u> <u>Impactor</u> <u>Punch</u> <u>Riveter</u> <u>Porta-Power</u> <u>Brake/Form</u> <u>Nibbler</u>	<u>Pry</u> <u>Impactor</u> 1. Hammer 2. Stud Setter 3. Others <u>Punch</u> <u>Riveter</u> <u>Porta-Power</u> <u>Linear Grinder</u> <u>Linear File</u> <u>Brake/Form</u> <u>Nibbler</u>

TABLE III. TYPE OF DRIVE CLASSIFICATION

REACTIONLESS ROTARY DRIVE	MULTIPLE (ROTARY DRIVEN) IMPACT DEVICES	DIRECT GAS POWER	ONE-SHOT GAS POWER	DIRECT ELECTRIC POWER
<u>Saw</u> 1. Sabre Saw 2. Jig Saw 3. Circular Saw 4. Friction Heat Saw Rotary-Reciprocating Saw <u>Welder Drive</u> <u>Shear</u> 1. Reciprocating 2. Rotating - One Wheel 3. Rotating - Two Wheels <u>General Drive Mechanism</u> <u>Drill</u> <u>Hole Saw</u> <u>Torque</u> 1. Nut Runner 2. Torque Wrench 3. Screwdriver 4. Aero-Space Fastener a. Huckbolt b. Betabolt c. Hi-Shear Fastener <u>Rotary File</u> <u>Grinder/Sander</u> <u>Nibbler</u> <u>Push-Pull Device (Mechanical Porta-Power)</u> <u>Prying Device (Mechanical Porta-Power)</u> <u>Clamping Device</u> <u>Screw Drive for Pull Riveter</u> <u>Nut Splitter</u> <u>Other</u>	<u>Impactor</u> <u>Chisel</u> <u>Multiple Shot Punch</u> <u>Upset Riveter</u> <u>Other</u>	<u>Pneumatic Push-Pull (Porta-Power)</u> <u>Pneumatic Forming Brake</u> <u>Pneumatic Clamp</u> <u>Other</u> 1. Shelter Erection 2. Propulsion 3. Etc.	<u>Punch</u> <u>Riveter</u> <u>Shear</u> <u>Restraint Attacher</u> <u>Stud Setter</u> <u>Other</u>	<u>Work Lights</u> <u>Cameras</u> <u>Resistance Heating for Bonding</u> <u>Welder Supply</u> <u>Magnetomotive Forming Tools</u> <u>Other</u>

CLASSIFICATION OF POWER SOURCES FOR SPACE TOOLS

In this section, the various power sources for space tools are listed, along with the type of prime mover necessary to transform the power into mechanical output. Wherever the information is available, approximate power-to-weight ratios are given. Table IV shows this in chart form.

TABLE IV. CLASSIFICATION OF POWER SOURCES FOR SPACE TOOLS

ELECTRICAL POWER	GAS POWER - CONTINUOUS/PULSED	SINGLE SHOT GAS POWER SOURCE
<u>Power Source</u> 1. Batteries a. Primary (One Shot) [110 whr/kg (50 whr/lb)] [4] b. Rechargeable [143-220 whr/kg (65-100 whr/lb) - Silver-Zinc] [4] 2. Fuel Cells [880 whr/kg (400 whr/lb)] [4] a. Alone b. With Batteries 3. Solar Panels with Batteries [8.8-26.4 whr/kg (4-12 whr/lb)] [4] 4. Chemical Powered Mechanical Generators [660 whr/kg (300 whr/lb)] [4] 5. Nuclear-Electric Generators (Thermionic/Thermoelectric) 6. Other <u>Prime Mover</u> 1. DC Motor 2. AC Motor 3. Magnetomotive Forming Devices	<u>Power Source</u> 1. Monopropellant Gas Generator 2. Biopropellant Gas Generator 3. Solid Propellant Gas Generator 4. Thermite-Steam Generator 5. Nuclear Steam Generator 6. Other <u>Prime Mover</u> 1. Turbine 2. Axial Piston Motor 3. Other	<u>Power Source</u> 1. Solid Propellant Cartridges 2. Monopropellant Cartridges 3. Thermite-Steam Cartridges 4. Other <u>Prime Mover</u> 1. Turbine 2. Axial Piston Motor 3. Single Piston Impactor 4. Other

EVALUATION OF THE VARIOUS POWER SOURCES

The following requirements will be used as a guide in evaluating the available power sources listed above:

1. Safety

- a. Temperature
- b. Exhaust products
- c. Spent fuel disposal
- d. Ejecta caused by exhaust
- e. Possibility of fouling cable or hose
- f. Handling of fuel
- g. Other

2. Total Power and Power to Mass Requirements

- a. Storage volume - weight for used and unused fuel
- b. Power to Mass ratio
- c. Recharge capability
- d. Other

3. Other Considerations

- a. Emergency power source - will power be available in an emergency?
- b. Availability of power source on spacecraft
- c. Other uses of power module (e. g. , gas erected structures, lighting)
- d. Minimum reaction requirements
- e. Other

In consideration of the items in this listing, the following discussions are in order:

1. Safety

a. Temperature. Any part of the space tool which could come in contact with the astronaut must not become hotter than 394°K ($+250^{\circ}\text{F}$) nor colder than 116°K (-250°F) during the longest expected use of the tool [5]. It is preferable that the temperature of the tool not come close to either of these extremes for extended use; probably $294^{\circ}\text{K} \pm 283^{\circ}\text{K}$ ($70^{\circ}\text{F} \pm 50^{\circ}\text{F}$), or from 266°K to 322°K ($+20^{\circ}\text{F}$ to $+120^{\circ}\text{F}$), would be safer and impose less load on the space suit environmental control system. In addition, the exhaust products must lie within this temperature range if there is a chance that they might impinge upon the astronaut.

b. Exhaust products. The exhaust must be noncorrosive and noncontaminating if there is chance of its impinging upon the astronaut or upon a part of the spacecraft where it could cause damage by corrosion or become a source of contamination. In addition, if the tool is used within the confines of the spacecraft pressure cabin, the exhaust gases must be nontoxic and impose no additional load upon the environment control system. In effect, this rules out all gas powered or gas producing power tools for use within the spacecraft. Thus, for internal cabin use, we are already restricted to electric power or possibly thermite-heated steam power if the exhaust steam is retained within the tool.

c. Spent fuel disposal. If fuel cartridges are used, some provision must be made for their safe disposal. If, as in the case of thermite fuel cartridges, they are extremely hot, then they must either be allowed time to cool, or be disposable and storable without having the astronaut come in contact with them. If the spent cartridges are stored in the spacecraft, they must be resealed to insure that no spent material gets loose in the cabin. If there is a possibility of any material getting out, the toxicity of the spent cartridge must be considered.

d. Ejecta caused by exhaust. The space tool power source must be designed so that its exhaust does not blow chips or cuttings away from the work site. It also must not damage adjacent equipment, wiring, etc.

e. Cable fouling. If there is a cable or hose connecting the tool to either a remote power source or the astronaut, the possibility of fouling this cable must be considered. The effect of cutting or pulling loose this cable or hose on the astronaut's safety must be evaluated. For example, in the case of a monopropellant hydrazine-powered tool with a remote tank, cutting of the hydrazine line would result in contamination and possible blinding of the astronaut. A suitably armored hose could be provided, but at a substantial weight penalty.

f. Handling of fuel. If the fuel is toxic, corrosive, or contaminating, either it must be in sealed containers, or provision must be made for remote filling of the supply tank. For example, if the hydrazine from the maneuvering unit is to be used, all connections must assure no possibility of leakage during a filling operation.

2. Total Power and Power to Mass Requirements

a. Storage volume to weight for used and unused fuel. In the case of packaged fuel, the weight and volume of the fuel cartridges makes the theoretical power to weight to volume ratio worse. If the used fuel cartridges are retained, storage space must be provided for them, possibly in the same area where the unused cartridges were stored. It is obvious that packaged fuel does not offer as attractive a solution to extensive space work as does bulk fuel, at least as far as weight and volume are concerned.

b. Power to mass ratio. Naturally, the system with the highest power/mass ratio is the most attractive from the standpoint of launching it. Ultimately, the power/mass ratio will be one of the major deciding factors in the evaluation of a candidate space power tool system.

c. Recharge capability. Provisions must be made to insure that the power supply, when depleted, can be recharged. For the case of batteries, suitable chargers must be supplied, powered by either solar cells, fuel cells, or other available means. The fuel cells must be kept supplied with fuel, and replacement batteries must be stocked. If the space tool is a self-contained hydrazine-powered unit, for example, a refill capability must be designed in for any extended use period. For long term usage, bulk loading of the monopropellant has advantages over cartridge loading, but both types must be considered. Certain systems naturally lend themselves more readily to recharging than others.

3. Other Considerations

a. Emergency power source. In case of an emergency power failure, the space tool should be useable, but this may not be a realistic situation. Generally, a major power failure on a spacecraft would so jeopardize the mission that the chance of such a failure would be minimized by having several redundant power systems. It may not, therefore, be realistic to consider performing operations under a condition of power failure. It would amount to an unnecessary capability, although most of the tool systems proposed would work, at least for a short time, without spacecraft power. A completely

packaged power tool system, such as the thermite system, might be considered to have an advantage here, but it is slight. Both the electrical system and the hot gas system require spacecraft power for recharge - either battery recharge or electrical power to open valves. So far there are very few hand operated valves on any existing spacecraft.

b. Availability of power source on existing spacecraft. Part of the recharge/use capability of a space power tool system depends on power supplies or fuel being normally aboard the spacecraft - either fuel/solar cells for battery recharging, or monopropellant fuel for the gas generator powered tool. The advantage of using existing power/fuel is that existing systems can merely be increased in size rather than duplicated, a situation which will cause a significant weight reduction. The increased capability system will, in general, weigh less than the duplicated system.

c. Other uses of the power module. Other (non-direct tool) uses of the power module can often aid in the completion of a mission. As an example, a gas generator power supply could provide gas for an inflatable structure, if the exhaust gases were compatible with the structure materials and possible habitation restrictions. Direct electric power is necessary for lighting, but could also be used to heat restraint attachment adhesives or to power magnetomotive forming, punching, or fastening tools.

d. Minimum reaction requirements. Gas-powered tools must be designed in such a way that the exhaust gases do not generate reaction forces. Such power tools can present a very difficult design problem. Naturally, electric tools, having no exhaust gases, do not have this problem.

DISCUSSION AND ANALYSIS

General

For a tool system to be useable within the cabin, it must meet the following requirements: absence of non-life-supporting exhaust gases; no severe temperature load imposed on environment system; and no chips, cuttings, or ejecta. These requirements eliminate the gas-powered tools (exhaust gases and temperature), the thermite steam-powered tools (temperature), and the cartridge powered tools (exhaust gases). The saws, drills, files, sanders, chisels, and grinders are eliminated because of the

chips and cuttings. A tool utilizing chemical bonding can also present a problem because of the fumes. We are thus led to the conclusion that only electrical power (either from sealed batteries or from an external power source - fuel cell, reactor, etc.) or hand power will be safe for use within the spacecraft, and, furthermore, certain tools must be prohibited because of chips, cuttings, ejecta, etc.

The result of this restriction on power tools for interior use leads us to three choices for tool system power:

1. Use no power tools in spacecraft interior. Redesign existing hand tools and tether systems to do a better job in the zero gravity environment. Since for most jobs within the spacecraft a spacesuit will not be necessary, hand tools can be used a little easier. The power tool with the best power/mass ratio can then be chosen for the outside tasks. The advantage of this approach is that only one power tool system need be developed. The disadvantage is that no power tools are available for inside work.

2. Use only electrical power tools, which are suitable both inside and outside the spacecraft. The advantage of this is that only one power tool need be developed, and it can be used anywhere; the disadvantage is that for long term usage, other power tools may have a better power/mass ratio.

3. Use electrical power inside, and whichever unit gives the best power/mass ratio outside. This approach could have weight advantages over the second alternative for sufficiently long missions. The disadvantage is that two power units need to be developed. Since the object of this study is to investigate space power tools, we will leave the first alternative (no power tool inside) with no further discussion. We next need to consider the point at which the weight of some advanced power tool system plus an inside electrical system crosses over a pure inside-outside electrical system.

First we briefly consider the power cord problem. For a gas generator system to have significant weight advantages, it must make bulk use of the generant. This means a remote tank and pressurization system (since a remote gas generator and hot high pressure gas line is less attractive than a cold generant pressure line from a source to a generator mounted on the space tool). It seems reasonable to assume that an electrical wire will be no more problem than a pressure hose - actually, it is less of a problem, since it can be made smaller, less subject to damage and thus safer, and more flexible.

We assume that both electrical power and monopropellant will be available on the spacecraft or on the workshop, and that furthermore we need not consider a major electrical power failure as this is such an extreme case as to constitute a mission failure. In any case, both a battery-powered tool and a propellant gas-powered tool would be useable as long as their self-contained power lasted. Probably neither could be recharged in the event of a power failure.

We concluded previously that 186 w to 373 w (0.25 to 0.5 horsepower) would be adequate to power all the candidate tool modules, and that a rotary type prime mover offered advantages over other types in that it was capable of driving the largest number of tools. We will therefore consider candidate power systems which are capable of producing approximately 186 w to 373 w (0.25 to 0.5 horsepower) in a rotary device.

Candidate Systems

1. Martin Tool [6] - Electric Motor

a. Specifications

Weight of Power Supply: 2.21 kg (5 pounds)

Weight of Prime Mover: 2.56 kg (5.62 pounds)

Power Supply Capacity: 163 watt hours

Power to Weight of Power Supply: 71.7 whr/kg (32.6 whr/lb)

Type of Power Supply: commercial silver-zinc rechargeable batteries.

Type of Prime Mover: permanent magnet 12-Vdc motor with minimum reaction features.

b. Computations

Use time to depletion: at 373 w (0.5 horsepower) -rate, 1572 seconds or 26.2 minutes at 746 w (1 horsepower) rate, 786 seconds or 13.1 minutes; or 586 356 w seconds (786 horsepower seconds), 9773 w minutes (13.1 horsepower minutes).

2. Rocket Power Inc. [7] - Gas Turbine

a. Specifications

Weight of Power Supply: unspecified

Weight of Prime Mover: 2.3 kg (5.15 pounds)

Power Requirements: 0.0112 pound per second gas flow at 500 psig and 810° R (350° F). This assumes $\gamma = 1.33$, $R = 83$ foot pounds per pound per ° R.

Power Output: The turbine produces approximately 438w (0.587 shaft horsepower) at 25 750 revolutions per minute. This is reduced to 377 w (0.505 horsepower) and 45 revolutions per minute in the reduction and reversing gears.

Type of Power Supply: unspecified type of gas generator.

Type of Prime Mover: two-stage axial-flow turbine with reduction gear and gas bearings.

b. Computations

If we assume a monopropellant hydrazine gas generator, with the low turbine inlet temperature, our molecular weight will be about 11 [7]; this changes R to approximately 140 foot pounds per pound per ° R, and changes the mass flow rate to 0.77 times 0.0112 pound per second or 0.00862 pound per second. We therefore have a flow rate of $0.00862/11$ moles/second or 0.000784 moles per second, since we have 359 standard cubic feet (SCF) per mole at standard temperature and pressure (STP) or 0.000784 times 359, resulting in 0.2815 SCF per second. If we assume that for a sufficiently large gas generator we can get 20 SCF per pound of gas generator [8], we get $\frac{0.2815}{20}$ pounds of gas generator required per second, or 0.01407 pound per second for 0.505 horsepower. Thus 5 pounds of gas generator would give us $\frac{5}{0.01407}$ times 0.505 horsepower second, or 179.5 horsepower second or 2.99 horsepower minute. This looks extremely unfavorable for this candidate system, but two things should be noted before we reject it completely. First, the turbine performance could be greatly improved by using a higher inlet pressure, and second, the efficiency of the reduction gears could be slightly improved.

3. Vickers Inc. [9] - Axial Piston Motor

a. Specifications

Weight of Power Source: not specified.

Weight of Prime Mover: 0.91 kg (2 pounds) estimated.

Input Requirements: 2100 psig gas from 233°K to 1310°K (-40°F to 1900°F) at approximately 0.0034 pound per second for approximately 418 w (0.56 horsepower) output at 7000 revolutions per minute. Composition of gas is unspecified.

Type of Power Source: unspecified type of gas generator.

Type of Prime Mover: bent axis type axial piston motor. These figures are estimated from a 4117 w, 1.68 kg (5.6-horsepower, 3.7-pound) unit.

b. Computations

If we again assume a molecular weight of 11 and 20 SCF per pound of gas generator 7, we see that we need $\frac{0.0034 \text{ pound per second}}{11 \text{ pounds per mole}} \times 359$ SCF per mole, which results in 0.111 SCF per second, 0.0055 pound of gas generator per second. Therefore, for 418 w (0.56 horsepower) and 2.27 kg (5 pounds) we get $0.5 \times \frac{0.56}{0.0055}$, which results in 379 714 w seconds or 6326 w minutes (509 horsepower seconds or 8.48 horsepower minutes). Again, this does not look favorable compared to electric power.

4. General Precision, Inc. (Kearfott Div.) [10] - Thermite Fueled Steam Generator

5. Quantic Industries, Inc. [11] - Monopropellant Powered Impulse Device

6. Remington Arms Company [12] - Cartridge Driven Impact Devices

While all of these proposed devices have high power to weight ratios, none of them includes a device to convert the power into rotary motion. Since this is probably the main source of inefficiency, it is very hard to assign a realistic total power to weight ratio. Comments about this general problem are presented in the next section.

7. Advanced Electric Tool

If we consider the additional advantages that fuel cells provide over batteries, we see that electrical tools can offer significant weight advantages over other systems. As an example, an Apollo type fuel cell has a power density of approximately 880 whr/kg (400 watt hours per pound) as opposed to the best silver zinc battery's maximum of 220 whr/kg (100 watt hours per pound) [4]. The actual batteries used in the Martin tool have a power density of 71.7 whr/kg (32.6 watt hours per pound). In addition, a lighter motor can be designed which would not be just an off-the-shelf item, the basis of the existing Martin tool.

8. Advanced Piston Motor

It is conceivable that some type of piston motor utilizing either high-energy monopropellant gas or steam from a thermite-fueled source could be made with an efficiency high enough so that it would exhibit an overall power to weight ratio advantage. Let us assume that the power to weight ratio for the proposed system is p pounds per horsepower hour and the system weighs q pounds without propellant. We then construct a graph showing total system weight versus time of operation at a 373 w (0.5-horsepower) rate where total system weight includes the weight of the pure electrical system (for inside work) plus the weight of the proposed high energy outside system. Figure 3 shows an example of a trade off study for a typical candidate power system versus electric systems with batteries and fuel cells. It is necessary to estimate the ratio of hours of inside to outside work in order to construct these graphs. If it is desired, this can be solved fairly simply and in an analytic manner. We use the following symbols:

- a = Mass (weight) of pure electric system without batteries - kilograms (pounds).
- b = Mass (weight) of pure electric power supplies per 373 whr (0.5 horsepower hour) - kg per 373 whr (pounds per 0.5 horsepower hour).
- q = Mass (weight) of proposed power system less power supply - kilograms (pounds).
- p = Mass (weight) of power supply per 373 whr (0.5 horsepower hour) - kg per 373 whr (pounds per 0.5 horsepower hour).
- S = Ratio of inside hours to outside hours $S = \frac{\text{No. inside hours}}{\text{No. outside hours}}$

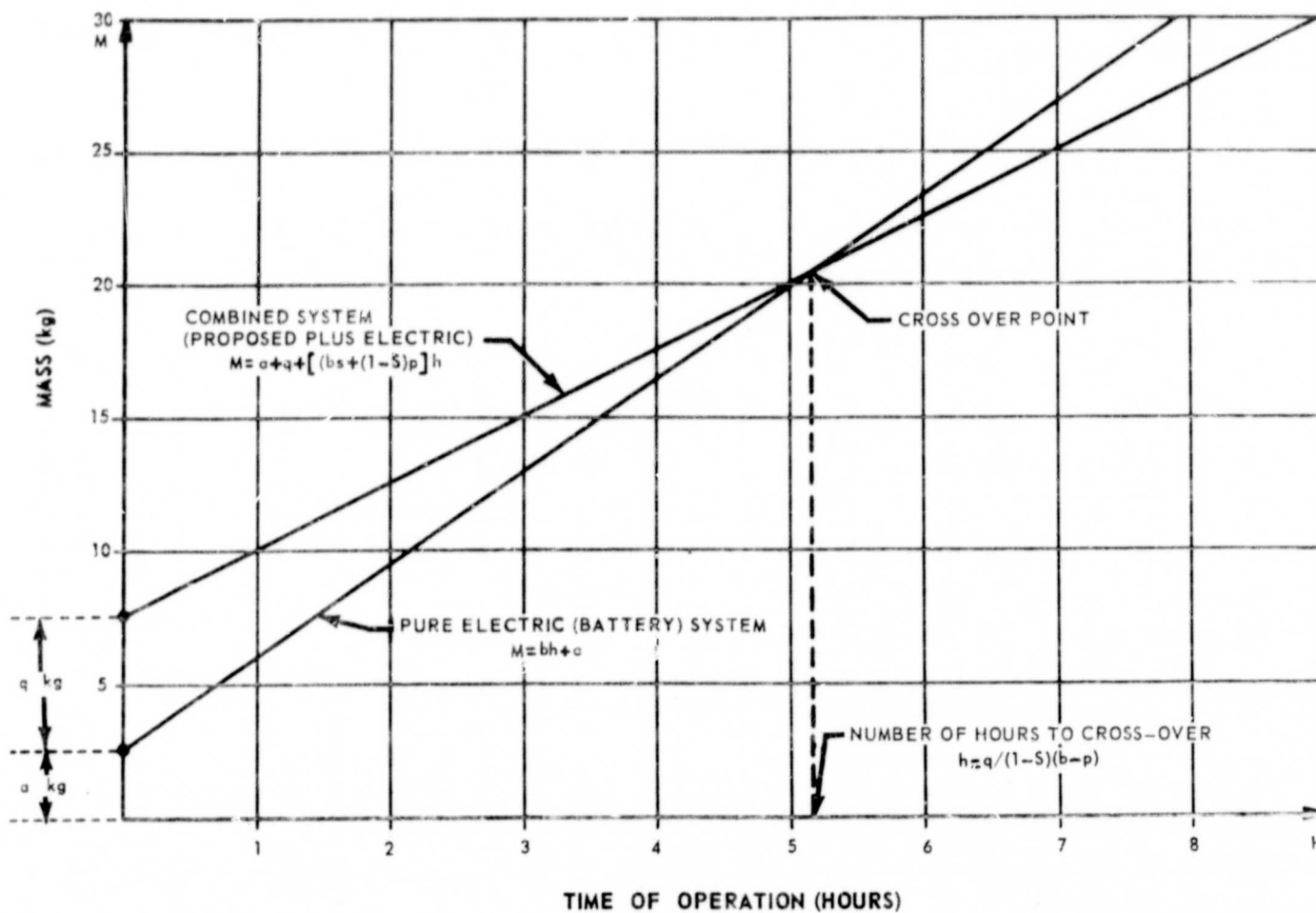


FIGURE 3. TRADEOFF STUDY: HYPOTHETICAL PROPOSED SYSTEM VERSUS PURE ELECTRIC SYSTEM

M_1 = Total system mass (weight), pure electronic system kg (lbs).

M_2 = Total system mass (weight), electric inside system plus proposed (outside) system kilograms (pounds).

h = Time, hours [hours].

For a pure electric system, the mass (M_1) for a time h hours of operation will be:

$$M_1 = a + bh \quad (\text{kilograms}). \quad (1)$$

For a combined system, in h hours, Sh hours will be devoted to inside work, and $(1-S)h$ hours will be devoted to outside work. Thus the total system mass (M_2) for h hours will be:

$$M_2 = a + bSh + q + p(1-S)h \quad (\text{kilograms}). \quad (2)$$

We wish to know the number of hours at which the mass of the two systems will be equal - or, for what h is $M_1 = M_2$? Equating (1) and (2), we get

$$a + bh = a + bSh + q + p(1-S)h \quad (\text{kilograms}) \quad (3)$$

or:

$$q = (1-S)bh - (1-S)ph \quad (\text{kilograms}) \quad (4)$$

$$q = (1-S)(b - p)h \quad (\text{kilograms}). \quad (5)$$

Solving for h :

$$h = \frac{q}{(1-S)(b-p)} \quad (\text{hours}). \quad (6)$$

It is obvious from equation (6) that there is no point in proposing a system that does not have a better power to mass ratio than a pure electric system. [Better power to mass implies lower p , which is kg per 373 whr (pounds per 0.5 horsepower hour)].

Typical values of a and b might be:

$$a = 2.55 \text{ kg (5.62 pounds) (Martin Tool) [6]}$$

$$\text{for batteries: } b = 5.21 \text{ kg/373 whr (11.45 pounds/0.5 horsepower hour) (Ag-Zn battery) [6]}$$

$$\text{or, for fuel cells: } b = 0.434 \text{ kg/373 whr (0.955 pound/0.5 horsepower hour) (Apollo fuel cell) [12]}$$

Actually, a practical electrical system would probably be a compromise, using both batteries and fuel cells, and thus would have a power to weight ratio somewhere between the two extreme cases.

According to Koelle [13], turbines are only suitable for several hundred hours of operation, and because of clearances, Reynolds number, etc., are not

suitable for power levels below 746 w (1 horsepower). Piston engines are slightly better in the low horsepower range, but still not really useful. This is borne out by the comparative figures given earlier, namely, that the axial piston motor has approximately twice the power to weight ratio of the turbine, but not nearly as high as that of an electric motor.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of existing or proposed space tool power sources, we conclude that an electrical powered rotary prime mover utilizing silver-zinc batteries and fuel cells offers significant power/mass advantages over any other proposed system. This surprising result is primarily caused by the difficulty in converting the tremendous thermal energy available in existing monopropellants into useful rotational mechanical power.

We recommend that emphasis be placed upon developing a purely electrical rotary-driven tool system for space use, at least until a new power system is proposed with a significantly better power to weight ratio than an electrical unit using batteries and fuel cells. It must be borne in mind that only electrically driven devices are suitable for use within the spacecraft interior, and that any exotic tool power system must also include provisions for electrical operation within the spacecraft.

We further recommend that some effort be devoted to examining the problems that an electrical tool will present (RFI, etc.) and also to determining whether DC or DC converted to AC is more suitable for tool power in terms of power/mass. In addition, the existing Martin power tool can be redesigned to reduce the weight and possibly increase the bearing and brush life in the hard vacuum of space.

Certain of the tool types mentioned in the classification section have not been commercially developed, although none of the types listed would be difficult to develop. The space porta-power and space crawler are examples of this class. If it is felt that these types will be valuable in space, then some effort could be expended in their development.

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